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Cost-effective opportunities for climate change mitigation in Indian agriculture

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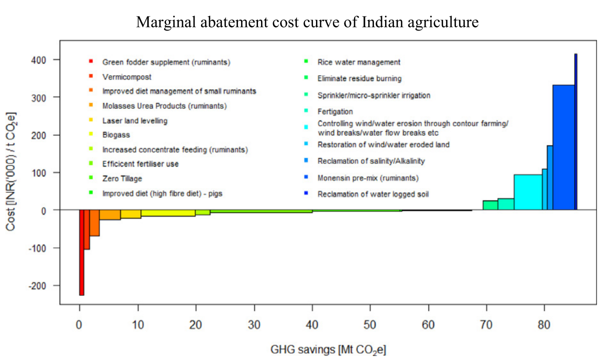
HIGHLIGHTS

- We estimated total carbon footprint of Indian agriculture together with mitigation potential and cost
- Indian agriculture has potential to mitigate 85.5 $MtCO_2e$ per year, 80% of which is delivered by cost-effective options
- Government should follow both carrot and stick approach for wide-scale promotion of these no-regret mitigation options

GRAPHICAL ABSTRACT



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ABSTRACT

Long-term changes in average temperatures, precipitation, and climate variability threaten agricultural production, food security, and the livelihoods of farming communities globally. Whilst adaptation to climate change is necessary to ensure food security and protect livelihoods of poor farmers, mitigation of greenhouse gas (GHG) emissions can lessen the extent of climate change and future needs for adaptation. Many agricultural practices can potentially mitigate GHG emissions without compromising food production. India is the third largest GHG emitter in the world where agriculture is responsible for 18% of total national emissions. India has identified agriculture as one of the priority sectors for GHG emission reduction in its Nationally Determined Contributions (NDCs). Identification of emission hotspots and cost-effective mitigation options in agriculture can inform the prioritisation of efforts to reduce emissions without compromising food and nutrition security.

We adopted a bottom-up approach to analyse GHG emissions using large datasets of India's ‘cost of cultivation survey’ and the ‘19th livestock census’ together with soil, climate and management data for each location. Mitigation measures and associated costs and benefits of adoption, derived from a variety of sources including the literature, stakeholder meetings and expert opinion, were presented in the form of Marginal Abatement Cost Curves (MACC). We estimated that by 2030, business-as-usual GHG emissions from the agricultural sector in

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India would be 515 Megatonne CO_2 equivalent ($MtCO_2e$) per year with a technical mitigation potential of 85.5 $MtCO_2e$ per year through adoption of various mitigation practices. About 80% of the technical mitigation potential could be achieved by adopting only cost-saving measures. Three mitigation options, i.e. efficient use of fertilizer, zero-tillage and rice-water management, could deliver more than 50% of the total technical abatement potential.

1. Introduction

Globally, agriculture faces the triple challenge of increasing production to meet the growing food demand, adapting to changing climatic conditions whilst reducing agricultural greenhouse gas (GHG) emissions where possible. Over the last fifty years, the increase in agricultural production to meet food demand of growing population have resulted in near doubling of GHG emissions from agriculture, forestry and fisheries (Smith et al., 2014). To feed a global population of 9.1 billion with current dietary patterns, overall food production is projected to increase by 70% between 2005 and 2050, resulting in a further 30% increase in global GHG emissions from agriculture (Tubiello et al., 2014). This growth in agriculture and associated emissions will occur mostly in Asian and African countries, where a high percentage of the population depends on agriculture and allied sectors for their livelihoods.

The 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) set a target to limit global warming to well below 2 °C above pre-industrial levels, with an aspiration target to limit warming to 1.5 °C. To realize this goal, a drastic reduction in global emissions is required. India is the third largest GHG emitter in the world, after China and the United States (https://wri.org/blog/2014/11/6-graphs-explain-world%E2%80%99s-top-10-emitters) and therefore has a major role to play in reducing global emissions and determining the future climate. India's Nationally Determined Contributions (NDCs) to the UNFCCC, pledges to reduce the emission intensity of its GDP by 33–35% by 2030 compared to 2005 levels (India's NDC to UNFCCC, http://www.moef.nic.in/climate-change-docs-and-publications).

The agricultural sector is responsible for 18% of gross national GHG emissions in India (INCCA, 2010) mainly through rice cultivation, livestock production, fertilizer use and burning of crop residues. India is currently experiencing a phase of rapid economic growth and demographic change. Per capita income has risen steadily since the 1980s and with this economic growth and an expected population of about 1.71 billion in 2050 (http://www.populstat.info/Asia/indiac.htm), food demand is expected to double by 2050 (FAO, 2014). Therefore, emissions from agriculture in India are expected to increase further in the future.

Given the significance of agriculture to total national emissions, India has identified agriculture and allied sectors as a priority area for emissions reduction in its NDC to the UNFCCC (Richards et al., 2016). The key starting point for assessing the mitigation potential of the agricultural sector is to quantify baseline emissions and analyse the major sources contributing to these emissions, taking into account variation in land use and production systems. Appropriate mitigation strategies can then be developed based on available technical options and their costs of implementation. This information can usefully inform policy developments that are consistent with national food security, economic development and environmental sustainability goals (Whittaker et al., 2013).

GHG emission inventories for India are available for years 1994, 2000, 2007 and 2012. The GHG platform of India, an Indian civil society initiative, also provides an independent analysis of emissions across key sectors including agriculture (http://ghgplatform-india.org). However, these estimates are largely based on activity data and emission factors (EFs) for a limited number of locations and so fail to capture the diversity of climate, soil and management conditions in Indian agriculture. To our knowledge, this is the first national-level study of GHG emissions from Indian agriculture that combines an analysis of agricultural emissions, which are sensitive to pedo-climatic and management conditions, with an evaluation of the cost-effectiveness of different mitigation strategies under a business-as-usual (BAU) and mitigation scenario. For the purpose of this paper the term 'agriculture' includes all activities associated with crop production, livestock husbandry and land management.

2. Methodology

2.1. Data sources

The crop production related data were taken from the household survey conducted by the Government of India (GoI) using multi-stage random sampling technique (http://eands.dacnet.nic.in). Districts within states, and villages within districts, formed the first and second stage unit of sampling, with the ultimate unit of data collection being the household (CSO, 2002). The districts and villages were selected to cover the major crops grown in the country (Table S2). Each plot was identified through geo-coordinates. Locations of households selected for the survey, which form the foundation of the activity data used in this analysis is given in Vetter et al. (2017) and also given in Fig. S1. Of various information collected in this survey, field specific information on tillage and crop establishment, crop management including water, fertilizer and residue management as well as grain and biomass yield were taken into account in the estimation of GHG emissions. Management information for crops which was not included in the GoI household survey was gathered from various other sources as described below. Data on temperature and rainfall corresponding to each field were obtained from the WorldClim global climate database (http://worldclim.org), and soil data (soil texture, soil organic carbon, soil pH, bulk density) were obtained from Shangguan et al. (2014). In rice plots, the water management before and during cultivation was determined based on Huke and Huke (1997), Gupta et al. (2009), Bhatia et al. (2013), and using expert judgement. After the harvest, agricultural residues are used for different purposes off-site (e.g. livestock feed, cooking fuel) or left in-situ. In some intensively cultivated areas, the crop residues left in the field after harvest are often burnt in-situ to facilitate cultivation of subsequent crops. State-level information on residue management of different crops, including burning, was obtained from Gadde et al. (2009) and Jain et al. (2014). The area under different crops in each state and union territory were taken from state agriculture departments, the Directorate of Economics and Statistics of GoI, IndiaStat website (http://www.indiastat.com) and FAOSTAT (FAOSTAT, 2018).

State-wise details of livestock by breed, age, sex and management type were obtained from the 19th livestock census of the Government of India (GOI, 2012). The information on livestock production system, body weight, feed consumption and *per-head* production of meat and milk were based on expert judgement from the National Dairy Research Institute (NDRI) of India and following relationships outlined in Herrero et al. (2013).

2.2. Models used to calculate GHG emissions

GHG emissions from crops were calculated using the Cool Farm Tool (CFT) (Hillier et al., 2011, CFT: https://www.coolfarmtool.org/). The CFT is a GHG emission calculator that allows users to estimate annual GHG emissions associated with the production of crops or livestock products (Hillier et al., 2011). It comprises a generic set of empirical models that are used to estimate full farm-gate product emissions constituting a mix of Tier 1, Tier 2, and simple Tier 3 approaches. The tool takes into account context-specific factors that influence GHG emissions such as pedo-climatic characteristics, production inputs and other management practices at field as well as farm level. The model provides total GHG emission per unit area as well as per unit of product allowing users to estimate the performance of production system from a GHG emission perspective both in terms of land-use efficiency and efficiency per unit of product.

For the current analysis, a version of the CFT scripted in Matlab (R2012a [7.14.0739], MathWorks, USA) was used to calculate the emissions for on-farm plots across India. GHG emissions from rice production were estimated using the method of Yan et al. (2005), which bases estimates of CH_4 emissions on several variables (i.e. soil pH, climate, organic amendment, pre-water regime, water regime). These factors were available at plot level in this study, but were not factored in to the IPCC Tier 1 method (IPCC, 2006). Background and fertilizer-induced N_2O emissions were calculated based on the updated nitrogen model of Stehfest and Bouwman (2006). Emissions from crop residues returned to the field were calculated using IPCC N_2O emission factors. Similarly, emissions from the production and transportation of fertilizer were based on Ecoinvent database (Ecoinvent Center, 2007). Changes in soil C due to tillage, manure and residue management are based on IPCC methodology as in Ogle et al. (2005) and Smith et al. (1997). Similarly, emissions of CO_2 from soil resulting from urea application or liming are estimated using IPCC methodology (IPCC, 2006).

GHG emissions from livestock husbandry were calculated using the approach of Herrero et al. (2013) which provided data on GHG emissions from enteric fermentation and manure management for several animal groups (i.e. ruminants, small ruminants, pigs and poultry), which was tailored to various livestock management systems under different agro-ecologies in India. National GHG emissions were calculated based on the average body weight of the livestock for different regions. Emissions arising from feed production were not included in this analysis as livestock feeding in India largely depends on crop by-products and concentrate, the environmental footprint of which is included in crop emissions. We accounted for only GHG emissions related to farm management, and did not account for processing, marketing or consumption post farm-gate. GHG emissions up to the farm-gate are reported in CO_2 equivalent (CO_2e) per ha of crops and per head for livestock using the 100 year global warming potentials (Climate Change, 2013).

For each crop and livestock type, state-level mean emission and standard deviation were obtained from the spatial model run using all available data-points within a state. The state means were then multiplied by state-level total area (for crops) and number of animals (for livestock) to obtain state totals. Emissions from all the states were summed-up to obtain total national emissions. To determine the uncertainty in our estimates, we calculated 95% confidence intervals (CI) for the state means using Eq. (1)

$$\mathrm{CI} = \overline{X} \mp t_{\alpha/2, n-1*} \frac{s}{\sqrt{n}} \tag{1}$$

where CI = Confidence Interval, $\overline{X}$ = mean emission, $t_{\alpha/2,\, n-1}$ = Inverse of student's t at 0.05 probability, s = sample standard deviation and n = number of samples within the state.

2.3. Stakeholder engagement

Stakeholders' workshops involving participants from different subsectors of Indian agriculture including crops, livestock and natural resource management were held on the 8th September and 11 September 2015 and attended by 15 to 20 delegates at each workshop. Included were representatives from state agriculture and livestock department, Indian Council of Agricultural Research (ICAR), Agricultural Technology Application Research Institute (ATARI) and subject matter specialists from university and research institutes. The main objectives of the stakeholder workshops were to:

- Present and critically review the data and preliminary analysis of GHG emissions by sub-sector;
- Identify the mitigation options that should be included in the mitigation scenario for 2030; and
- Based on the above develop a business-as-usual and mitigation scenario for GHG emissions in 2030 with the latter based on implementation of the mitigation options that are technically feasible but ambitious in terms of scale i.e. it is assumed that political and institutional conditions are conducive to wide-scale adoption.

The workshops were organised in two phases. The first phase consisted of an introduction to the project followed by a presentation of the preliminary results for GHG emissions by sub-sector and the data sources used to inform the analysis. The second phase consisted of a more structured discussion, guided by a checklist, on the development of a business-as-usual and ambitious mitigation scenario for 2030. This included discussion and agreement on the direction and magnitude of change in natural resource base (e.g. soil, water and degraded land), technologies and practices (e.g. for improved nutrient/water use efficiency, crop diversifications, mechanization, residue management, restoration of degraded land etc.) together with socio-economic and institutional/policy changes. The discussions on technical mitigation options, magnitude of their adoption under business-as-usual and mitigation scenarios, barriers to adoption and policy measures needed to overcome such barriers were used to construct GHG emission scenarios discussed in the following section. A further series of consultation meetings were held between January 2016 to August 2017 with subject matter specialists in agriculture, livestock and natural resource management, to sense-check and refine the mitigation scenarios developed at the stakeholder workshops.

2.4. Mitigation options, costs and benefits

Mitigation options considered in crop/livestock production and restoration of degraded land were derived from a number of sources including literature from studies in the region, options available within the CCAFS-MOT (Feliciano et al., 2017) and through stakeholder consultations and expert opinions. These together with their mitigation potential and cost of adoption are presented in Table 1. To develop GHG mitigation recommendations appropriate for India, the abatement potential of most of the mitigation options were taken from studies in India. For example, the mitigation potential of adopting zero-tillage, prevention of crop residue burning, improved water management for rice and adoption of laser land levelling were obtained respectively from Powlson et al. (2014), Feliciano et al. (2017) and Jat et al. (2015). Similarly, the mitigation potential of fertigation/micro-irrigation techniques were calculated taking into account the amount of fertilizer and water saved from these technologies based on the result of an on-station trial at Ludhiana (Rolaniya et al., 2016). GHG savings from efficient fertilizer management in crops, including that from the shift towards cleaner fertilizer production technology, were based on the options embedded in Feliciano et al. (2017). The cost of adopting mitigation options and additional benefits accrued through adoption of these options were calculated considering the cost of production inputs such as tillage, planting, seed, fertilizer, biocides, irrigation, harvesting and residue management. The cost of human labour for such management practices (e.g. tillage, seeding, irrigation, fertilizer/pesticide application, weeding, harvesting, residue management etc.) were calculated using minimum wage rates under the Indian labour law and person-days incurred to perform such activities per ha. The cost of fertilizer, fuel and electricity were based on current market prices in India (as of

Table 1
GHG mitigation options along with their mitigation potential and cost of adoption.[†]

GHG abatement options	Mitigation potential[a]	Gross cost of mitigation[b]	Net cost of mitigation[b]
Crops			
Improved water management in rice	2760	−1378	−3445
Adoption of zero-tillage	518 to 1796	−963 to −308	−1690 to 208
Stop residue burning	−3 to 522	−6278 to − 498	−6278 to − 498
Fertilizer production	57 to 529	Not considered	Not considered
Fertilizer consumption	47.83 to 198.46	−710 to −2327	−710 to −2327
Laser Land levelling	1284 to 3055	1000	−5188
Increase NUE through fertigation	170 to 4999	25,000	21,750
Sprinkler/micro-sprinkler irrigation	163 to 1276	10,000	8700
Livestock			
Green fodder supplement for large ruminants	32.23 to 38.84	2957 to 4106	−14,783 to −5493
Increased concentrate feeding for large ruminants	116.77 to 139.82	4654 to 6894	−2340 to 128
Monensin pre-mix for large ruminants	32.23 to 38.84	61,685	57,973 to 60,316
Molasses Urea Product (MUP) for large ruminants	116.77 to 139.82	1460	−5964 to −1278
High fiber diet for pigs	121.75	675	−325
Improved diet management for small ruminants	21.36	189	−1411
Improved Manure management of large ruminants	30.63	13,358	−2235
Biogas from large ruminants' manure	500.23	2960	−1751
Restoration of degraded lands			
Reclamation of salinity/Alkalinity through chemical amendment	495	85,000	85,000
Reclamation of water logged soil through sub-surface drainage	183	76,000	76,000
Restoration of wind/water eroded land through Jatropha plantation	275	1833	−2000
Restoration of wind/water eroded land through plantation	275	71,500	71,500
Controlling wind/water erosion through contour farming/wind breaks/water flow breaks etc.	275	45,500	26,000

[†] The range of values indicate the mitigation potential and costs when mitigation options are applied to multiple crops or livestock. When mitigation options are applied to a single crop or livestock a single value of mitigation potential and cost is given.
[a] kg CO_2e/ha/yr for options related to crop management and restoration of degraded land and kg CO_2e/head/yr for the options related to livestock management.
[b] INR/ha for options related to crop management and restoration of degraded land and INR/head for the options related to livestock management.

August 2017). The grain prices were taken from the minimum support price, as per India's agricultural price policy (as of August 2017).

Mitigation options for enteric methane emissions from livestock, along with their mitigation potential, were obtained from Sirohi et al. (2005) and Sirohi and Michaelowa (2008). The cost associated with the increased consumption of green fodder and concentrate and inclusion of feed additives (monensin pre-mix and molasses urea product) and additional benefits due to adoption of such practices were obtained from Sirohi et al. (2005), Sirohi and Michaelowa (2008), and through expert consultation. Establishment and management costs of vermicompost and biogas together with their benefits were taken from agriclinics and agribusiness centres of GoI's department of agriculture and Cooperatives (http://www.agriclinics.-net/modelProjects.htm).

Reclamation potential of saline, alkaline and water-logged soils and associated costs were derived from ICAR-CSSRI (2016a, 2016b). Costs and benefits of restoring wind/water eroded land through Jatropha plantation were obtained from Goswami et al. (2011). Similarly, cost of plantation in wind/water-degraded land and controlling such erosion through contour farming, wind breaks and water flow breaks were derived from Sreedevi et al. (2009). GHG mitigation through SOC change resulting from restoration of degraded land and prevention of erosion were obtained from Jat et al. (2016b). The scale of adoption of mitigation options under the two scenarios were obtained through expert judgement and further validated during the stakeholders workshops, as explained earlier.

2.5. GHG emission scenarios

We analysed GHG emissions and savings by 2030 under a Business-As-Usual (BAU) and a mitigation scenario as described below. Various abatement options for crop, livestock and restoration of degraded land, along with scale of adoption under the BAU and mitigation scenario are summarized Table S1.

Business-as-usual (BAU): This scenario assumes that no new policies are in-place that are designed explicitly to reduce GHG emissions. Here, projection of emissions for the year 2030 from crop and livestock production are based on a set of growth assumptions in agricultural development such as input consumption, technological development, area under crops and livestock number (ICAR, 2011). These expected changes in natural resources base, technological advances and policy reforms were validated through the stakeholder workshops.

Mitigation scenario: this takes the 'BAU' scenario for 2030, considers those mitigation options that are technically available now or will be available by 2030, and applies them at a scale based on their ambitious but feasible adoption given socio-economic trends and institutional/policy developments in India (e.g. NAAS, 2017; Tallis et al., 2017; http://www.soilhealth.dac.gov.in/). Some examples include improved water and nutrient management, adoption of energy-efficient technologies, replacing rice with upland crops in some areas, improved fertilizer production technologies (e.g. mandatory production of Neem Coated urea; FAI, 2017), and restoration of degraded land. Again, all the mitigation options and their scale of adoption under the mitigation scenario were evaluated during the stakeholder workshops, as explained earlier.

2.6. Marginal Abatement Cost Curve (MACC)

The Marginal Abatement Cost Curve (MACC) represents the relationship between the cost-effectiveness of different abatement options and the total amount of GHG abated. As such, the emission savings and associated cost/benefits are the differences in total emissions and cost/benefit under BAU and mitigation scenario. For the abatement options related to crops and restoration of degraded land, mitigation potential per ha (obtained through a spatial run of model) were applied to the respective areas under BAU and mitigation scenarios (Table S1) to calculate total GHG savings under the two scenarios. The total GHG saving under BAU and mitigation scenarios for livestock-related mitigation were obtained by multiplying the mitigation potential per head (obtained through the model run) by the number of respective livestock to which each mitigation option can be applied under the two scenarios (Table S1). A similar approach was followed to calculate gross and net cost of adopting mitigation options under the two scenarios i.e. unit cost multiplied by the total area or number of livestock to which the particular mitigation option can be applied. The gross cost considers the cost of adopting a given mitigation option, whereas the net cost also include associated benefits. The GHG saving and cost/benefit of adoption of each mitigation option were derived by subtracting total GHG saving and cost under BAU from that under the mitigation scenario. The cost/benefit values per unit of CO_2e abated were calculated by dividing total cost/benefit by the total GHG saving.

3. Results

3.1. Total GHG emissions

State-wise average GHG emission per ha (for crops) and per animal (for livestock) in India are presented in Supplementary Table S2. Across the states, GHG emission per ha was highest in rice (mean and 95% CI are 3188 and 1425–6335 kg CO_2e/ha, respectively) and sugarcane (mean and 95% CI are 3187 and 2167–4264 kg CO_2e/ha, respectively). Emissions from other upland crops ranged from 69 to 2773 kg CO_2e/ha. Similarly for livestock, GHG emissions per head were highest in buffalo (mean and 95% CI are 909 and 895–930 kg CO_2e/head, respectively) and cattle (mean and 95% CI are 761 and 749–779 kg CO_2e/head, respectively) whereas average emissions for small animals ranged from 141 to 295 kg CO_2/head.

Based on this analysis, we estimated that total emissions from Indian agriculture were ca. 481 Megatonne (Mt) CO_2e in 2012. For the purpose of this study, the term agriculture includes all arable and field crops, major livestock groups and land management. Crop and livestock production contributed 42% and 58% to total agricultural emissions, respectively. Fig. 1 shows total national emissions from crop and livestock together with the contribution from individual crop and livestock species. Cattle production was the most important source of emission followed by rice, buffalo, small ruminant and wheat production. Rice cultivation contributed over 52% of total crop-related emissions followed by wheat, cotton and sugarcane, which in total constituted about 80% of total crop emissions. Of the total livestock-related emissions, cattle production constituted the highest share followed by buffalo and sheep/goat. Cattle, buffalo, sheep and goat constituted 99% of total livestock-related emissions. Taking crop and livestock emissions combined, Uttar Pradesh was the highest GHG emitter followed by Andhra Pradesh, Madhya Pradesh, Maharashtra, Rajastan and West Bengal (Fig. 2). Total emissions from crop production were highest in Andhra Pradesh, Uttar Pradesh and Maharashtra followed by West Bengal, Madhya Pradesh and Punjab. Total emissions from livestock were highest in Uttar Pradesh (~46 Mt CO_2e) followed by Rajasthan, Madhya Pradesh and Andhra Pradesh (Fig. 2).

Emissions from paddy rice were highest in Andhra Pradesh followed by West Bengal, Assam and Tamil Nadu (Fig. 3). Paddy rice emission was also relatively higher in the states such as Uttar Pradesh, Karnataka and Orissa. Emissions arising from wheat production were much higher in Uttar Pradesh compared with other wheat producing states such as Punjab, Madhya Pradesh and Haryana (Fig. 3). Emissions due to production of sugarcane were highest in Maharashtra followed by Gujarat and Andhra Pradesh (Fig. 3). Similarly, emissions from cotton production were highest in Uttar Pradesh, followed by Maharashtra, Karnataka, Tamil Nadu and Andhra Pradesh (Fig. 3).

Emissions from buffalo production were highest in Uttar Pradesh followed by Rajasthan, Andhra Pradesh and Gujarat (Fig. 4). Similarly, emissions from cattle production were highest in Madhya Pradesh and Uttar Pradesh followed by West Bengal and Maharashtra (Fig. 4), whilst the highest emissions from goats and sheep were in Andhra Pradesh followed by Rajasthan and Karnataka (Fig. 4).

Among crops, rice had the greatest emissions intensity followed by cotton. Emissions intensity for rice was highest in Himanchal Pradesh (3.37 kg CO_2e per kg of grain) followed by Uttarakhand, Kerala, Assam and Karnataka, all having emissions intensities of 1–1.5 kg CO_2e per kg of grain (Fig. 5). Emissions intensity in wheat ranged from 0.25 to 0.58 kg CO_2e per kg grain, and was highest in Chhattisgarh followed by Himanchal Pradesh, Jharkhand and Maharashtra (Fig. 5). In the case of cotton, Andhra Pradesh, Maharasthra and Karnataka had higher emission intensities compared to other states (Fig. 5). All sugarcane producing states had similar emissions intensity from sugarcane production. For livestock, GHG emissions per head per year were highest for Buffalo (910 kg CO_2e) followed by cattle (762 kg CO_2e) and pigs (280 kg CO_2e), whilst annual per-head emissions from sheep and goat were, on average, 245 and 151 kg CO_2e, respectively (Table S2). On an average, this corresponded to the emission of 0.83, 0.31 and 0.51 kg CO_2e per litre milk yield from local cow, crossbred cow and buffalo, respectively and 12, 4.5 and 16 kg CO_2e per kg meat production from goat, pig and sheep, respectively.

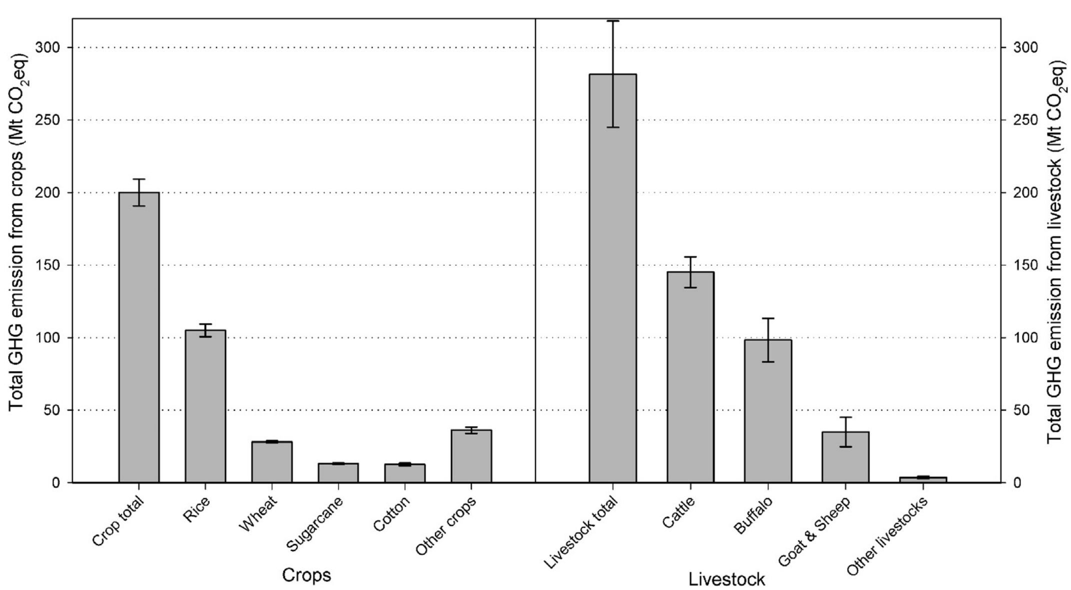

Fig. 1. Total national emissions from crops (left panel) and livestock (right panel). The error bars show 95% confidence interval.

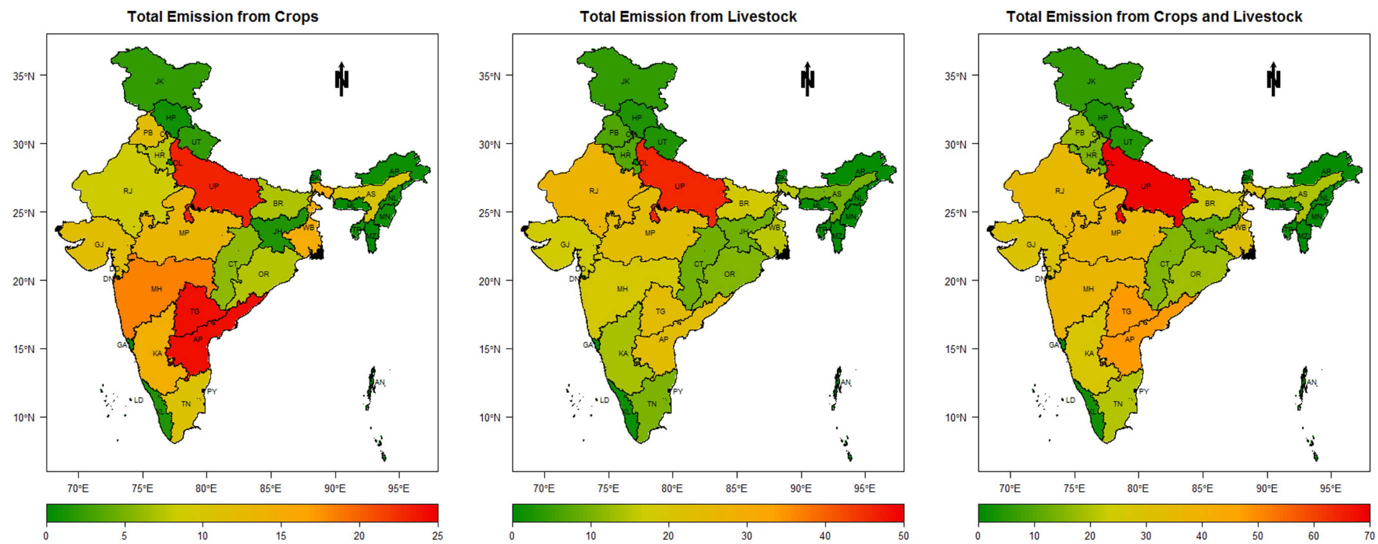

Fig. 2. State-wise distribution of total GHG emissions (Mt CO_2e) from crops, livestock and crop plus livestock combined. The full form of state names is given in supplementary Table S3. Andhra Pradesh in our study includes both Andhra Pradesh and Telangana combined.

3.2. GHG mitigation options in Indian agriculture

Improved management of agricultural land and livestock offers possibilities for mitigation through three mechanisms i.e. by reducing emissions, displacing emissions or by enhancing removals. The mitigation activities affect more than one gas, by more than one mechanism, sometimes in opposite ways, so that the net benefit depends on the combined effects on all gases. Many practices in agro-ecosystems have been advocated to mitigate emissions. The complete list of mitigation options included in this study, along with their mitigation potential and associated cost is given in Table 1. The crop abatement options identified include a range of improved agronomic practices that increase crop yields, promote soil carbon storage, as well as ensure best management practice for fertilizer, water and other resources, to increase resource-use-efficiencies, thereby reducing emissions associated with production inputs. For example, the use of slow-release fertilizer forms or nitrification inhibitors, and applying fertilizer at the right time and the right place for plant uptake increases nutrient-use-efficiencies. This not only reduces fertilizer-induced field emissions, but also reduces fertilizer consumption, thereby reducing emissions related to fertilizer production and transportation. The livestock-related mitigation options identified were: increment in green fodder and concentrate feeding for lactating cattle and buffalo, providing feed additives such as monensin and molasses urea products to cattle and buffalo, improved diet management of pigs and small ruminants (sheep and goat) and improved manure management. A large fraction of cultivable land in India has been degraded by erosion, excessive disturbance, organic matter loss, salinization, acidification or other processes that curtail productivity (ICAR, 2010). Restoration of such degraded land for crop production and vegetation establishment has the potential to increase C storage through increased photosynthesis and reduced soil erosion loss as well as reducing dependency on fossil fuels if grown with bioenergy crops, and so are also included as mitigation practices (Jat et al., 2016; Olsson and Ardo, 2002).

3.3. Mitigation potential and costs of adoption

Through this bottom-up analysis, we estimated that total emissions from major crops i.e. rice, wheat, maize, cotton and sugarcane (these crops constituted 80% of total crop emission) and livestock species i.e. cattle, buffalo, pig, sheep and goat (these livestock constituted 99% of total livestock-related emission) in India were 451 Megatonne (Mt)

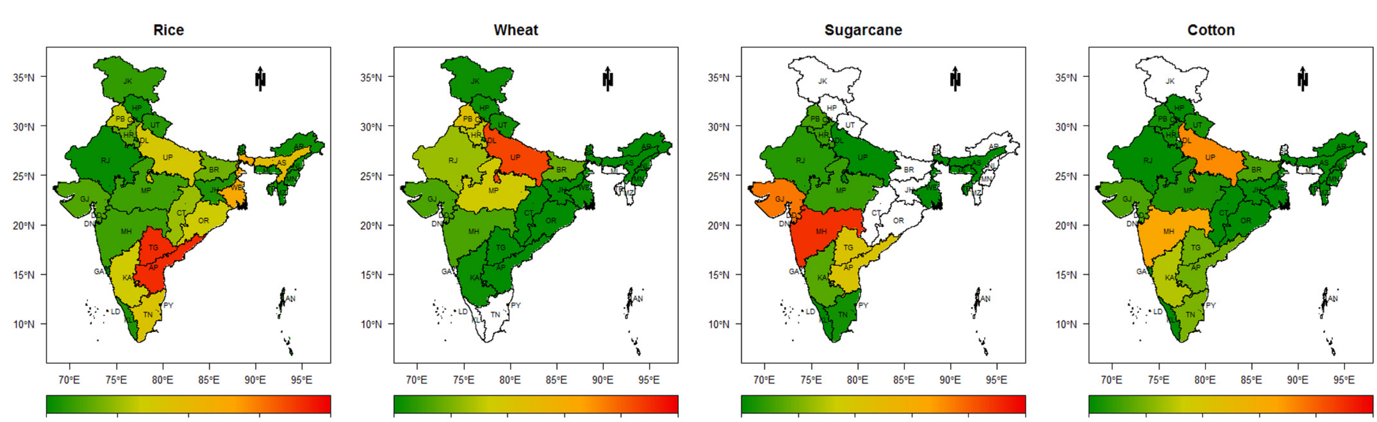

Fig. 3. State-wise distribution of GHG emissions (Mt CO_2e) from rice, wheat, cotton and sugarcane. At a national level, these four crops constituted 80% of total crop-related emissions. No colour means calculations were not done due to lack of activity data. The full form of the state names is given in supplementary Table S3. Andhra Pradesh in our study includes both Andhra Pradesh and Telangana combined.

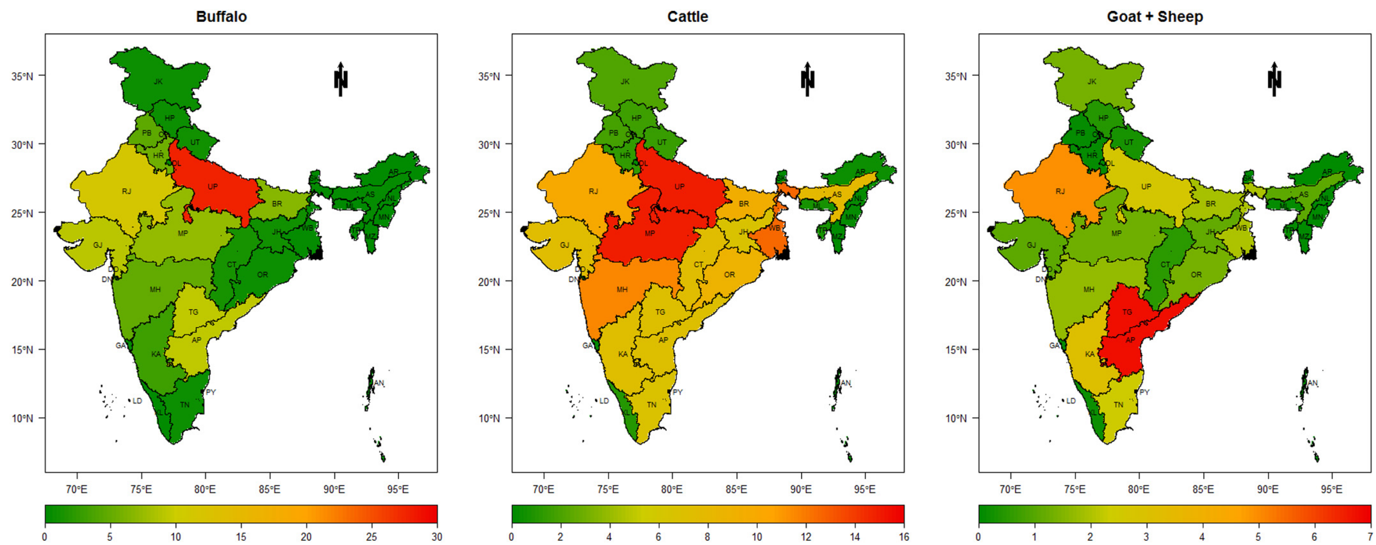

Fig. 4. State-wise distribution of GHG emissions (Mt CO_2e) from buffalo, cattle and sheep plus goat. At a national level, these four livestock types constituted 99% of total livestock related emissions. The full form of the state names is given in supplementary Table S3. Andhra Pradesh in our study includes both Andhra Pradesh and Telangana combined.

CO_2e in 2012. Under the BAU scenario with no mitigation, projected GHG emissions from these major crops and livestock species would be 489 $MtCO_2e$ in 2030 (total GHG emission from agriculture under BAU scenario would be 515 $MtCO_2e$), whereas emissions under the mitigation scenario would be 410 $MtCO_2e$, offering a technical mitigation potential of about 78.67 $MtCO_2e$ per year (Fig. 6). Considering the mitigation potential of restoring degraded land, total mitigation potential in the agricultural sector in India would be 85.5 $MtCO_2e$ per year (Figs. 7, 8). In other words, by 2030, about 18% of total emissions from agriculture could be abated by adopting technically feasible mitigation measures. Whilst sectoral targets to meet India's obligation under the Paris Agreement is yet to be set, if India's pledge (in its NDCs to the UNFCCC) to reduce its GDP emission intensity by 33–35% is distributed equally across economic sectors then the technically feasible mitigation measures identified in this study could deliver half of the agricultural sector's mitigation target.

As with the 2012 baseline, the most important sources of projected emissions under the BAU scenario were cattle followed by rice, buffalo and small ruminants. Although livestock production and rice cultivation are the major contributors of agricultural emissions, the highest mitigation potential was observed in rice (~36 $MtCO_2e\ yr^{-1}$) followed by buffalo (~14 $MtCO_2e\ yr^{-1}$), wheat (~11 $MtCO_2e\ yr^{-1}$) and cattle (~7 $MtCO_2e\ yr^{-1}$). Cotton and sugarcane each offered mitigation potential of about 5 $MtCO_2e\ yr^{-1}$. Technical mitigation potential from goat/sheep was about 2 $MtCO_2e\ yr^{-1}$.

Figs. 7 and 8 show the magnitude of GHG savings per year through adoption of various mitigation measures, together with the total cost (Fig. 7) and net cost (Fig. 8) per unit of CO_2e abated. Many of the mitigation measures employ currently available technologies and can be implemented immediately. The cost-beneficial measures have negative cost and appear below the x-axis on the left-hand side of the graph, whereas the cost-incurring measures appear above the x-axis, on the right-hand side of the graph. Of the total technical mitigation potential of 85.5 $MtCO_2e\ yr^{-1}$, about 45 $MtCO_2e$ was accounted for by measures that actually have a cost saving associated with adoption (Fig. 7). When the additional benefits of increased yield due to adoption of the mitigation measures were considered, about 80% of the technical mitigation potential (67.5 out of 85.5 $MtCO_2e$) could be achieved by cost-saving measures (Fig. 8). When yield benefits were considered, green fodder supplement to ruminant diets was the most cost-effective mitigation measure, followed by vermicomposting and improved diet management of small ruminants. Mitigation measures such as fertigation and micro-irrigation, various methods of restoring degraded land and feed additives in livestock appear to be cost-prohibitive even when considering the yield benefits, if any.

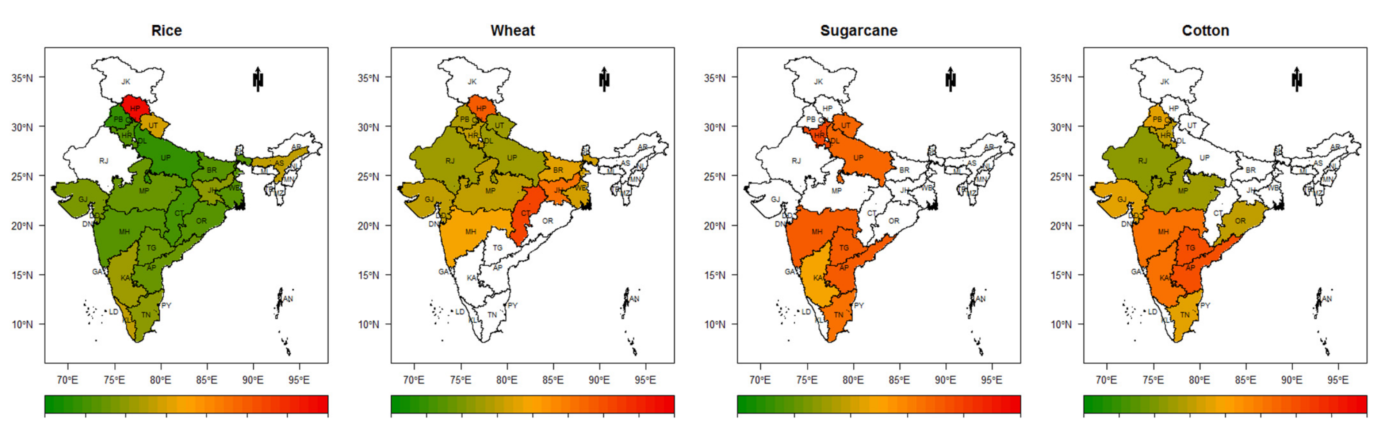

Fig. 5. Emission intensity (kg CO_2e/kg product) of rice, wheat, sugarcane and cotton in different states of India. No colour means calculations were not done due to lack of activity data. The full form of the state names is given in supplementary Table S3. Andhra Pradesh in our study includes both Andhra Pradesh and Telangana combined.

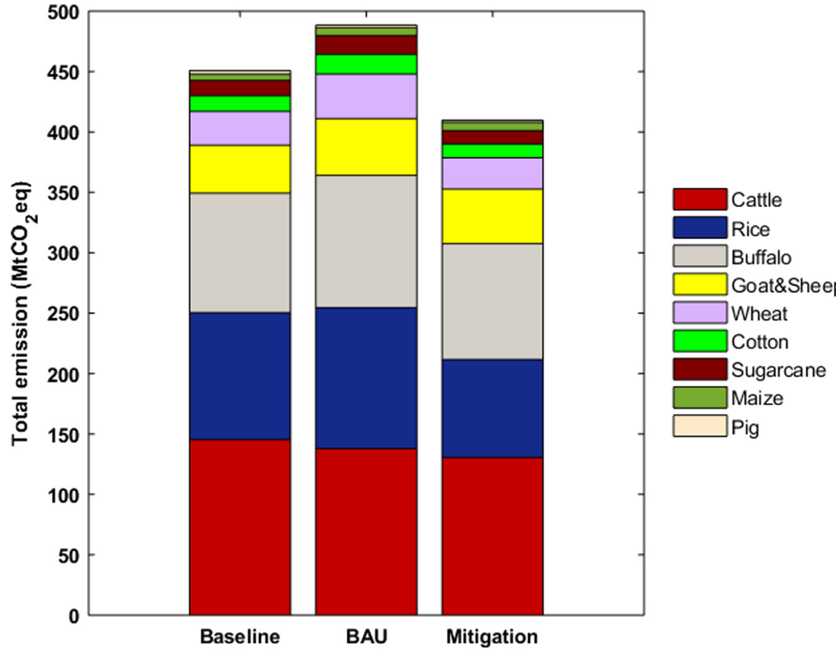

Fig. 6. Contribution of various crops and livestock species to total agricultural emissions in 2012 (baseline), and 2030 under business-as-usual (BAU) and the mitigation scenario.

3.4. Mitigation options in crop production

Our estimated technical mitigation potential of crop production in India was ca. 55.5 MtCO_2e year^{-1}. Of this, the mitigation potential of reduced fertilizer N consumption due to adoption of precision nutrient management technologies in India was ca. 17.5 MtCO_2e per year with cost saving of INR 6500 per tCO_2e abated (Fig. 7). Similarly, adoption of zero-tillage in rice, wheat, maize, cotton and sugarcane would provide abatement of about 15 MtCO_2e per year and also save 4200 INR per tonne of CO_2e abated. Improved water management in rice in India offered mitigation of ca. 12 MtCO_2e per year with a cost saving of INR 770 per tonne of CO_2e saved (Fig. 7). Considering the additional yield benefits, these mitigation options offered even more savings per unit of CO_2 abated (Fig. 8). Adoption of laser levelling in rice-wheat areas would result in mitigation of ca. 4 MtCO_2e per year with the nominal cost of INR 1940 per t of CO_2e saved without considering additional yield benefits, and INR 21947 saving per t CO_2e abated when additional yield benefits were considered (Figs. 7, 8). About 2 Mt CO_2e could be abated per year by stopping residue burning with the small cost of INR 680 per t CO_2 for residue management. Other water management options such as sprinkler, or micro-sprinkler irrigation and fertigation together, offered a technical mitigation potential of ca. 5.5 Mt CO_2e. However, these measures required large capital investment by farmers and cost more than INR 27000 per t CO_2e abated.

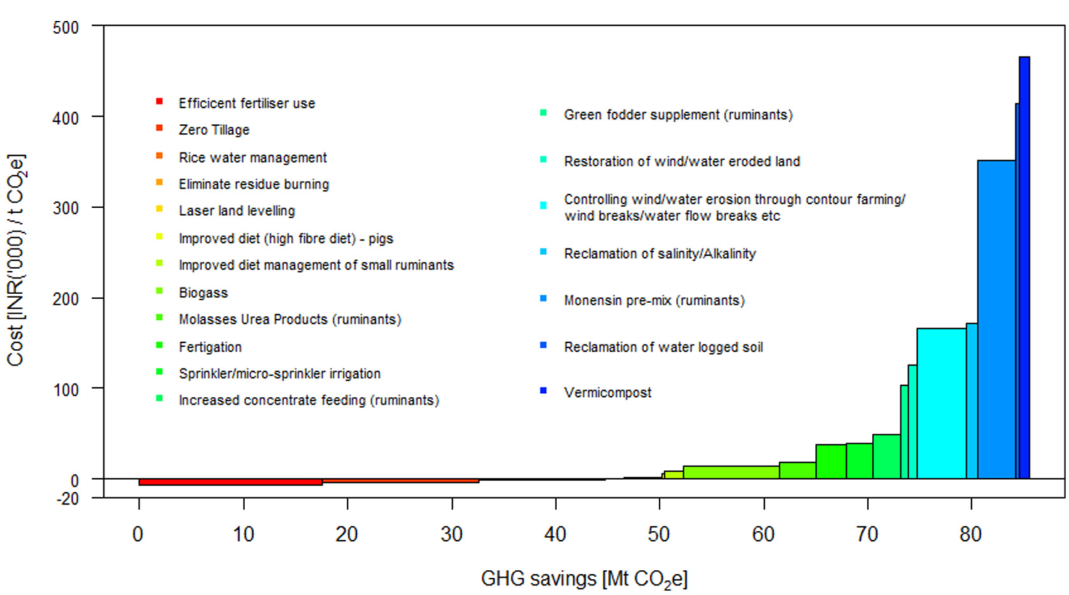

Fig. 7. Marginal Abatement Cost Curve of Indian agriculture without considering additional income from increased yield associated with the adoption of mitigation measures. The width of the bar represents the abatement potential from the mitigation option whereas height of the bar represents the average cost per unit of CO_2e abated. The area (height × width) of the bar represents the total cost of the action, i.e. how much it would cost altogether in order to deliver all of the CO_2e savings from the action.

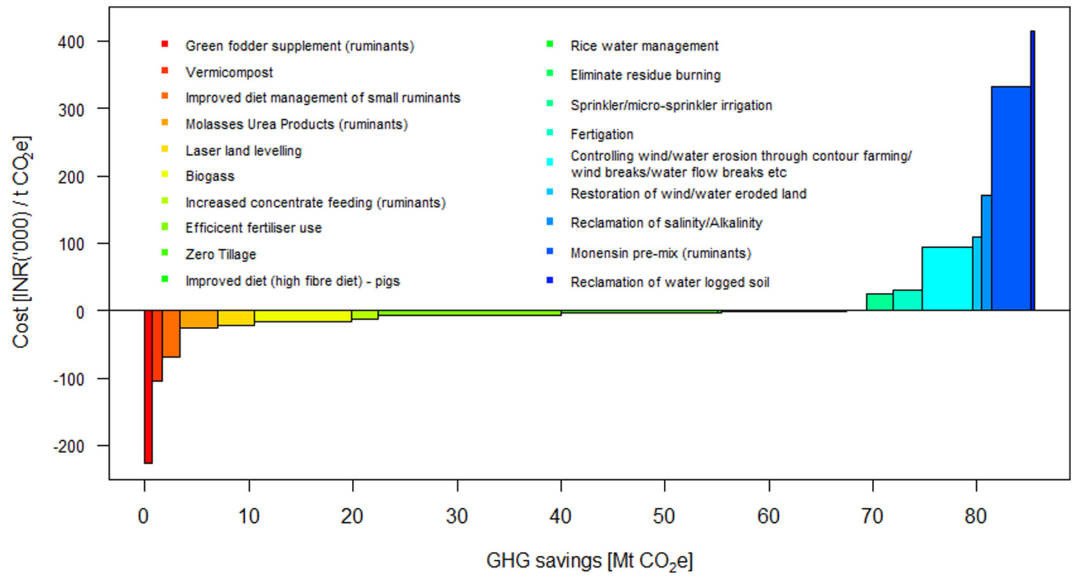

Fig. 8. Marginal Abatement Cost Curve of Indian agriculture considering additional yield benefit of adopting mitigation measures. The width of the bar represents the abatement potential from the mitigation option whereas height of the bar represents the average cost per unit of CO_2e abated. The area (height × width) of the bar represents the total cost of the action i.e. how much it would cost altogether in order to deliver all of the CO_2e savings from the action.

We also analysed the spatial distribution of the mitigation potential of efficient fertilizer use and rice-water management in order to identify mitigation hotspots at the scale at which policies are implemented in India. Our estimate shows that per-year GHG mitigation potential through reduced fertilizer consumption through precision nutrient management was highest in Uttar Pradesh (ca. 3.15 MtCO_2e) followed by Andhra Pradesh (2.04 MtCO_2e), Maharasthra (1.72 MtCO_2e) and Punjab (1.5 MtCO_2e) (Fig. 9). Mitigation potential through reduced fertilizer consumption in Gujarat, Karnataka, Madhya Pradesh, Haryana, Bihar, Rajasthan, West Bengal and Tamil Nadu would be between 0.7 and 1 MtCO_2e per year, and less than 0.5 MtCO_2e per year in other states.

In the case of water management in rice, the highest mitigation potential would lie in Andhra Pradesh (3.81 MtCO_2e) followed by Tamil Nadu (1.81 MtCO_2e), Orissa (1.54 MtCO_2e) and West Bengal (1.23 MtCO_2e) (Fig. 10). In Karnataka, Uttar Pradesh, Assam, Punjab and Bihar, this option would have the potential to save between 0.42 and 0.84 MtCO_2e emissions, whilst the remaining states would deliver less than 0.25 MtCO_2e savings (Fig. 10).

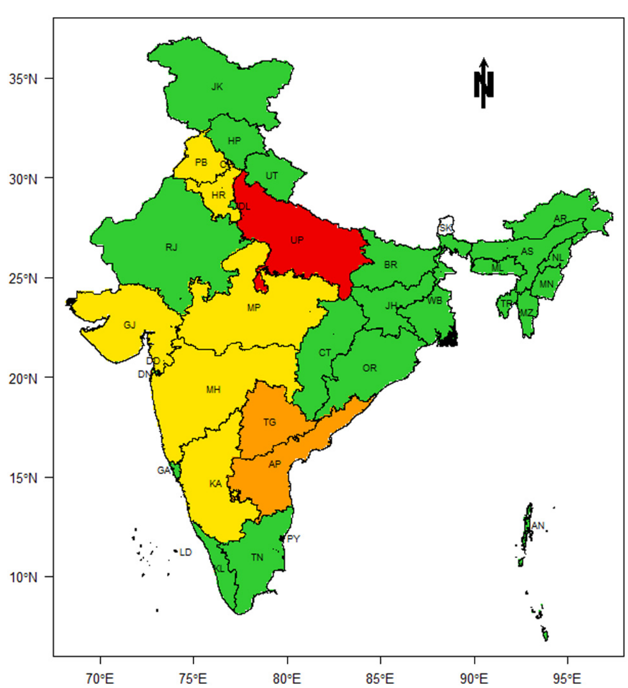

Fig. 9. Spatial distribution of GHG mitigation potential (MtCO_2e per year) through improved fertilizer management in India. The full form of the state names is given in supplementary Table S3. Andhra Pradesh in our study includes both Andhra Pradesh and Telangana combined.

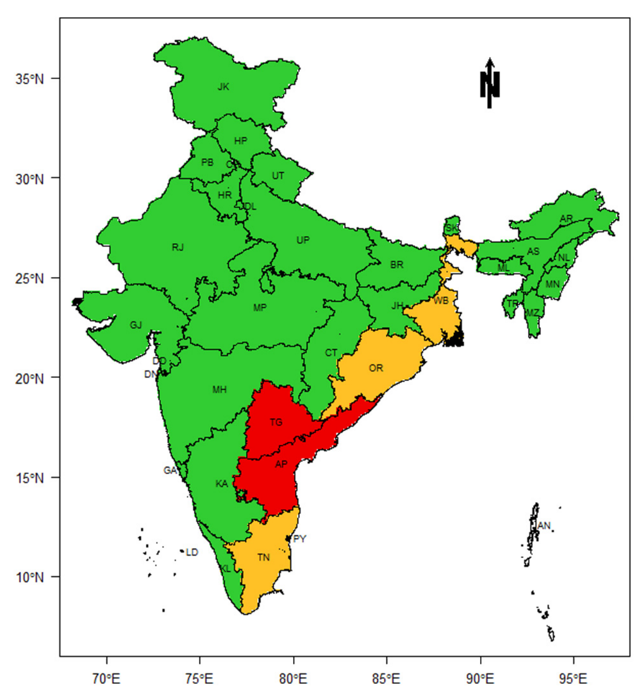

Fig. 10. Spatial distribution of GHG mitigation potential (MtCO_2e per year) through improved water management in rice. The full form of the state names is given in supplementary Table S3. Andhra Pradesh in our study includes both Andhra Pradesh and Telangana combined.

3.5. Mitigation options in the livestock sector

Improved feed digestibility through the provision of highly digestible fodder (e.g. green fodder) and inclusion of energy-dense food (i.e. increased concentrate feeding) have considerable potential for mitigating GHG emissions from the livestock sector in India. Green fodder supplement and increased concentrate in the rations of ruminants would have potential to mitigate ca. 3.4 $MtCO_2e$ per year. Although adoption of these measures would incur an additional cost (Fig. 7), these options, particularly green fodder supplement, appeared to be highly cost-effective when additional yield benefits were considered (Fig. 8). Use of feed additives such as monensin pre-mix and molasses urea products for ruminants together would offer a technical mitigation potential of ca. 7.2 $MtCO_2e$ although immediate adoption of monensin pre-mix would be cost-prohibitive in India (Figs. 7, 8). Improved manure management through establishment of large biogas plants had the potential to save ca. 9.3 $MtCO_2e$ per year. Although this option involved large capital investment (Fig. 7), inclusion of additional benefits from biogas output would make this option cost-effective (Fig. 8). Other GHG mitigation options from the livestock sector in India include dietary management of pigs and small ruminants (ca. 2 $MtCO_2e$) and improved manure management through vermicomposting (ca. 1 $MtCO_2e$) (Figs. 7, 8).

3.6. Mitigation through restoration of degraded land

The practices that reclaim productivity of degraded land such as plantation with multipurpose tree species and bioenergy crops can enhance soil carbon sequestration and substitute fossil fuels to some extent. Similarly, reclamation of saline, alkaline or water-logged soil can make additional land available for crop production or increase the productivity of agricultural crops, leading to increased carbon sequestration in vegetation and soil. The technical mitigation potential of restoring degraded land in India would be ca. 7 $MtCO_2e$ per year, but most of these options are cost prohibitive, even with a current price of carbon under carbon trading schemes (Figs. 7, 8).

4. Discussion

4.1. Total agricultural emissions compared to other estimates

Our estimate of total GHG emission from agricultural sector (461 Mt CO_2e) in India was slightly higher than the estimate of the Government of India (372 $MtCO_2e$; INCCA, 2010) and that of the India GHG platform (347 $MtCO_2e$; http://www.ghgplatform-india.org/) but smaller than FAO's estimate (744 Mt CO_2e; http://www.fao.org/faostat/en/#data/GT). However, the estimates of the Government of India and the India GHG-platform were derived from a simple inventory approach using activity data and emission factors, whereas our analysis involved a detailed bottom-up analysis using crop/livestock management, soil and climatic information distributed across all of India. Furthermore, our analysis followed a semi-life cycle approach that accounts for emissions from production up to the farm gate. For example, the emissions associated with production and transportation of fertilizer were included in our study, whereas they were not considered as agricultural emissions in national inventories. In our study, CH_4 emission from rice production was based on the approach of Yan et al. (2005) which considers pre-season water status, current water regimes, soil organic carbon, organic amendment and their interaction with various soil and climatic factors. This approach allows a high level of sensitivity to climatic conditions and soil properties, especially to soil pH and hence a better representation of growing conditions in India. FAO's estimate was much higher because it also considered emission associated with all energy used in agriculture.

In our analysis, livestock production contributed a slightly higher share (58%) to total agricultural emissions than did crop production (42%), in agreement with other estimates. Higher total emissions in states such as Uttar Pradesh, Andhra Pradesh, Madhya Pradesh, Maharashtra, Rajasthan and West Bengal mainly reflected the larger area under crops and larger livestock population in these states compared with other states. Higher crop emissions in states such as Andhra Pradesh, West Bengal and Punjab were mainly due to the larger area under rice cultivation. Similarly, higher crop emissions in states such as Maharashtra, Madhya Pradesh and Uttar Pradesh were mainly due to the larger area under cotton and sugarcane. Higher crop emission intensities in the states such as Himanchal Pradesh, Uttarakhand, Jharkhand and Chhattisgarh reflects lower crop yield in these states as compared to others.

4.2. GHG mitigation options, potential and cost of adoption

Croplands in India are intensively managed, and offer many opportunities to impose practices that reduce net emissions of GHGs. All the crops and soil management practices aimed towards increasing efficiency of water, nutrients, energy and other production inputs, and those, which increase crop production, lead to GHG mitigation (Sapkota et al., 2017a). For example, adopting zero-tillage in crop production offers GHG mitigation by enhancing carbon sequestration as well as reducing fuel consumption. Since soil disturbance tends to stimulate soil C losses through enhanced decomposition and erosion, reducing tillage operations in agriculture often results in soil C gain, although effects can be small (Powlson et al., 2016) and variable (Baker et al., 2007). In rice, no-tillage affects emissions of both CH_4 and N_2O, and in an opposing way, such that the net effect is negligible (Sapkota et al., 2015), with the result that any soil carbon gain can be considered a net mitigation. Similarly, avoiding the burning of crop residues also avoids emission of aerosols and GHGs generated from fire, and also enhances soil carbon (Sapkota et al., 2017b), all leading to GHG mitigation.

Nutrient-use-efficiency (NUE) not only increases crop yield, but also minimizes environmental problems through reduced emissions or leaching. Nitrogen input-output relationship at different N rates and associated GHG emission intensity (Fig. 11) demonstrate that the higher the proportion of applied N taken up by crops the lower the emission intensity. This was particularly evident for upland crops but not so for rice where methane management is crucial. It should be noted that N input through biological N fixation and N deposition has not been accounted for in our calculation. In general, NUE of crops is very low in India, i.e. about 30% (Farnworth et al., 2017; Tewatia et al., 2017) compared with other countries. This shows that there is great potential for GHG mitigation through improved nutrient-use-efficiency by adopting various approaches of precision nutrient management, such as adjusting the application rates based on a precise estimate of plant demand, using the right form of fertilizer, and applying fertilizer using correct methods at the time when the plant needs it.

Effective irrigation management in crops contributes to GHG mitigation by reduced water consumption and associated energy use for irrigation, by increased yields and residue returns (Lal, 2004), and by directly reducing CH_4 emissions from rice fields (Wassmann et al., 2004). Converting continuously flooded rice areas into alternate wetting and drying and promotion of laser levelling of fields (Jat et al., 2015), micro-irrigation and fertigation for effective water/nutrient management are some of the promising scalable technologies with considerable mitigation potential (Figs. 7, 8). Laser land levelling provides a GHG mitigation opportunity through reduced cultivation time and associated fuel consumption and also from reduced water and fertilizer use due to increased resource use efficiency (Jat et al., 2015).

Other water management options, such as sprinkler, or micro-sprinkler irrigation and fertigation contribute to GHG mitigation by reducing water consumption and associated energy use, increasing water-use-efficiency, and increasing crop yield and residue return (Rolaniya et al., 2016). However, these technologies increase the energy demand, and emissions associated with this has not been accounted for

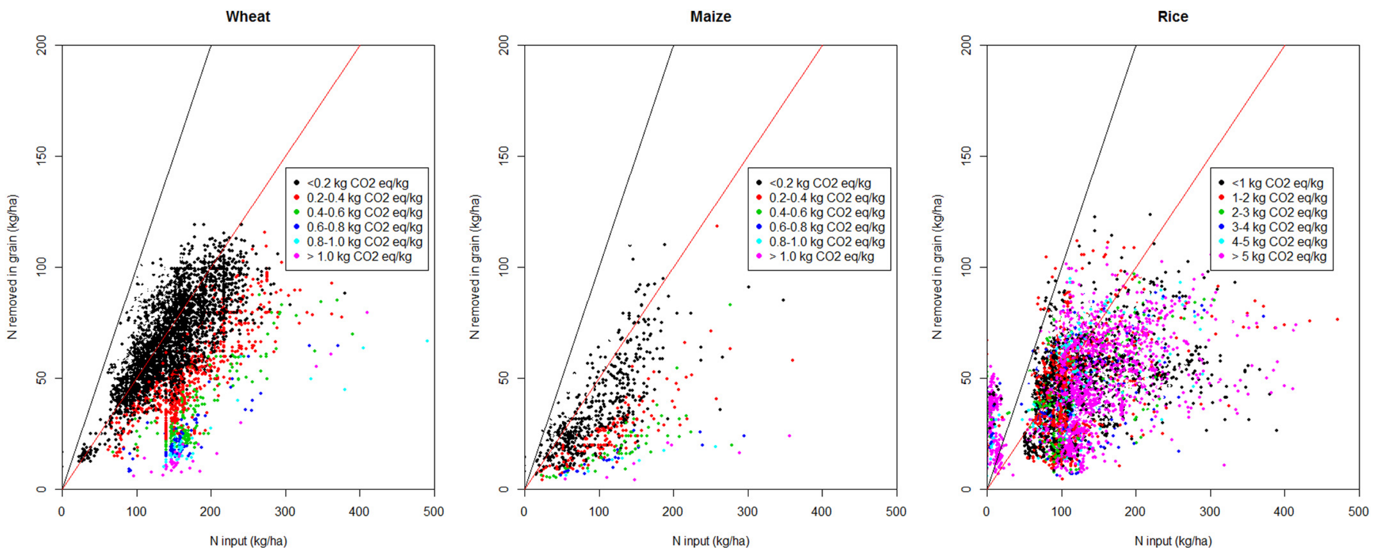

Fig. 11. Nitrogen input-output relationship at different N rates in wheat, maize and rice, and associated GHG emission intensities where the colour scheme indicates the range from low to high emission intensity. The lines are for 50% and 100% N uptake.

in our analysis. Also, these measures require large capital investment by farmers and cost more than INR 27000 per t CO_2e abated. However, given their large adaptation and mitigation potential, they might be good candidates for scaling under climate finance project such as the Green Climate Fund.

Supply-side mitigation options in the livestock sector include a range of diet and other management interventions that improve the efficiency of feed conversion, increase livestock productivity and reduce emissions. Improved feed digestibility through the provision of highly digestible fodder (e.g. green fodder), and inclusion of energy-dense food (i.e. increased concentrate feeding), have considerable potential for mitigating GHG emissions from the livestock sector of India with less developed production systems and very little grains fed to animals. By adopting these strategies to increase livestock productivity, it is feasible for India to meet future demand for livestock products without increasing the numbers of livestock, thus helping to realize estimated GHG mitigation as compared to the BAU scenario of an increased livestock population. Similarly, use of feed additives such as monensin pre-mix and molasses urea products for ruminants have been shown to decrease CH_4 emissions (Sirohi et al., 2005). Although addition of these feed additives have good technical mitigation potential (7.2 $MtCO_2$e), their immediate adoption in India is cost-prohibitive, even after considering additional yield benefits (Fig. 8). Improved dietary management of pigs and small ruminants can potentially be cost-effective mitigation measures in India, with combined mitigation potential of about 2 $MtCO_2$e year^{-1}. India has a huge potential to reduce manure-related GHG emissions through establishment of biogas plants. This measure requires a longer-term commitment and capital outlay, in addition to an initial establishment cost. Nevertheless, this option appears to be cost-effective when benefits of energy produced are taken into account (Fig. 8), and appropriate policy and financing mechanisms, such as the Green Climate Fund could be used to incentivise its uptake.

As food demand in India will continue to grow, displacement of food production by using agricultural land for forestation or bioenergy crops will threaten food security and lead to higher food prices. A large fraction of agricultural land in India has been degraded by erosion, water logging, excessive disturbance, salinization, acidification and other processes (ICAR, 2010). The country has a huge potential to restore and stabilize carbon in such degraded lands through forestation and bioenergy systems (Sochacki et al., 2012). Similarly, reclamation of saline, alkaline or water-logged soils can make additional land available for crop production, or increase the productivity of agricultural crops, leading to increased carbon sequestration in vegetation and soil (ICAR-CSSRI, 2016a, 2016b). As there are no direct incentives to restore such land, linking such initiatives with carbon markets and payments for ecosystem services may provide some capital for this. However, as the carbon abatement costs of these mitigation options are higher than the current international carbon price (Fig. 8), the GoI would need to make an investment to realize the benefit at watershed or catchment scales.

Our study suggests that 80% of the total technical mitigation potential (67.5 out of 85.5 $MtCO_2$e year^{-1}) in Indian agriculture can be obtained by adopting cost-beneficial mitigation options. Most of these measures are annual measures, which means that they do not require more than one-year of commitment on the part of farmers. However, realization of the abatement potential of individual measures will, be dependent on the extent of adoption by individual farmers. In principle, farmers should already be adopting these apparent win-win measures without any additional incentives but given t adoption at scale is not taking place it suggests that there are other barriers to overcome (Bustamante et al., 2014). Reasonable efforts have been made in the present study to construct realistic adoption scenarios of these practices/technologies, taking into account current trends and government priorities, and further refining them in the light of stakeholder feedback. It should be noted, however, that farmers' adoption of any practice is difficult to predict and largely depends on the socio-political environment under which farmer operates (Sapkota et al., 2017a). A better understanding of the socio-political environment and farmers' behaviours in relation to adoption of these cost-beneficial GHG mitigation measures would help in designing appropriate policies, consistent with food security and sustainable development goals. For example, due to government subsidy, urea is the cheapest source of fertilizer N in India. As a result, urea accounts for 82% of total nitrogen consumed in India, 100% of which is broadcast in field, resulting in huge losses through direct and indirect emissions. Applying slow-release fertilizers or avoiding broadcast-application and shifting towards drill-application, could deliver large emission savings. To achieve more widespread adoption of these cost-effective mitigation measures, the GoI could consider adopting a "carrot-and-stick" approach, using a combination of appropriate policy, incentives and awareness mechanisms. Further, mitigation potential of many of these measures will be vulnerable to climate variability and extremes.

Currently, very little research addresses how mitigation measures can be made more resilient to these potential impacts and should be the priority area for future research.

5. Conclusion

In this study, we estimated the total carbon footprint of Indian Agriculture following a bottom-up approach to identify the emission hotspots and mitigation options along with associated costs. We estimated that total emissions from Indian agriculture was 481 $MtCO_2e$ in 2012 of which crops and livestock contributed 42% and 58%, respectively. Through adoption of technically feasible mitigation options, the total mitigation potential in the agricultural sector in India, including restoration of degraded land, would be 85.5 $MtCO_2e$ per year. In other words, by 2030, about 18% of total emissions from agriculture could be abated by adopting technically feasible mitigation measures. Our study suggests that 80% of the total technical mitigation potential (67.5 out of 85.5 $MtCO_2e\ year^{-1}$) in Indian agriculture can be obtained by adopting cost-beneficial mitigation options. Although reasonable efforts have been made in this study to construct realistic adoption scenarios of the mitigation practices, realization of this mitigation potential will largely depend on the extent of adoption by farmers. Given that adoption of these apparently win-win options are not currently taking place at scale, the government of India will need to take both a carrot and stick approach to incentivising farmers through a combination of appropriate policy measures and incentive mechanisms to ensure wide-scale adoption of these mitigation options consistent with its food security and GHG emission reduction goal.

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Conflict of interest

The authors declare no conflict of interest.

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